THE MINERALIZATION AT CLIFTON–MORENCI

LOUIS E. REBER, JR

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THE MINERALIZATION AT CLIFTON-MORENCI.

Louis E. Reber, Jr.

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This paper presents a study of the mineralization associated with the intrusive stock to which are attributed the ore-deposits of the Clifton-Morenci district. From detailed microscopic and field study results are brought out bearing on the nature of the various phases of mineralization or rock alteration, and particularly on their mutual relationship and relation to the igneous intrusive. Contact alteration is contrasted with hydrothermal alteration, and the two types of hydrothermal alteration, sericitization and propylitization, are compared; lastly evidences bearing on the source of solutions effecting the mineralization are discussed and interpreted.

SOURCES OF MATERIAL.

The writer spent four months in the Clifton-Morenci district in the summer of 1915, and during the following winter some time was devoted to the study of a very comprehensive suite of specimens there collected, including numerous thin and polished sections of this material.

The Professional Paper by Lindgren[1] which appeared in 1905 includes practically all the published results of geological study of this district. This work necessarily forms a starting point

[1] U. S. G. S. Prof. Paper 43.

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for any later investigation. The general descriptive and explanatory matter here summarized is to be found in more detail in that paper.

At the time Lindgren completed his work on the Clifton-Morenci district it would have been difficult to add anything to that detailed and exhaustive study. Since then, however, a large amount of development work has been done in the mines; also the results of investigations in other districts have suggested new possibilities in regard to the relations which may exist between the processes of magmatic differentiation, ore-deposition, and rock-alteration. Therefore it is believed that further study of this relationship as exemplified in the Clifton-Morenci district is warranted.

GENERAL GEOLOGY.

The Clifton-Morenci district lies in the southern part of Greenlee county in southeastern Arizona, close to the New Mexico line and about 150 miles north of the international boundary. It belongs to that group of districts to which in recent years the name "porphyry copper camps" has been popularly applied. Like many geological terms which come into vogue in mining circles, this term has a somewhat indefinite meaning. At Morenci, however, it has a more exact significance than in certain other localities. That is to say: the bulk of the ore minerals occur in disseminated particles or veinlets in porphyry, though usually associated with some larger veins; and the ore-bodies owe their commercial value to chalcocitization by the processes of secondary enrichment.

The country rocks of the region are pre-Cambrian granite, Paleozoic and Cretaceous sediments, and the younger intrusives. Fig. 28 is a geological map showing the areal distribution, and Fig. 29 is a columnar section showing diagrammatically the thickness and sequence of the various formations.

The Paleozoic system which is apparently comformable throughout, is separated from the underlying pre-Cambrian granite by a great unconformity. It comprises about 200 feet of sandstone or quartzite of Cambrian age, 380 feet of Cambro-

Ordovician limestone, 175 feet of impure limestone and calcareous shale which is believed to be of Devonian age, and 170 feet

FIG. 28. Generalized Geologic Map of the Clifton Quadrangle.

of Mississippian limestone. At the top of this series is an important erosional disconformity, though there is slight structural

unconformity between this system and the overlying formation. A banded shale and sandstone formation of early Cretaceous age

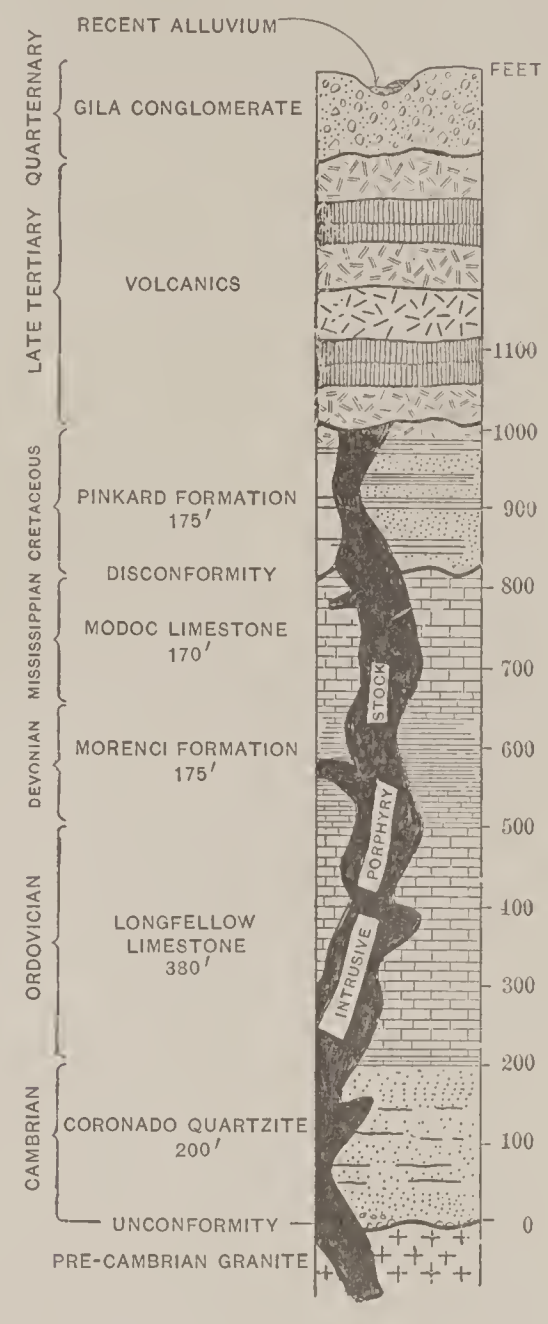

FIG. 29. Columnar Section for the Clifton Morenci District.

thickness of 175 feet of this has been preserved below the present is the sole representative of the Mesozoic system. A maximum erosion surface.

The sediments and underlying pre-Cambrian granite have been intruded by a mass of granite-monzonite-diorite porphyry which is exposed over an area extending about seven miles in a northeast south-west direction. The rock is granite porphyry in the northeast and diorite porphyry in the southwest, with a monzonitic phase intermediate. Associated with the intermediate or

monzonitic phase of the porphyry is a dark rock which has been found in several mines, but not extensively on the surface. It was not exposed when Lindgren was in the district, and Tovote[1] refers to it as diabase, as tiny apatite needles sometimes give it a diabasic appearance. Microscopic study has shown this dark material to include two rock types: one, composed largely of finely felted green mica, pyrite, and apatite, believed to represent a basic segregation in the porphyry (fig. 3) is minutely intruded by the other, a quartz-orthoclase-micropegmatite (fig. 7), the dark appearance of which is due to an unusual brown pigment in the feldspar.

The main intrusive mass is classed as a stock, though some laccolithic bodies extend to the southwest. The intrusion of this porphyry stock is held responsible for the origin of the mineralizing solutions instrumental in forming the copper ores.

Outside the main mass of porphyry are numerous dikes of the same material, disposed more or less radially. With these dikes there are a few diabasic ones which are known to cut the porphyry, though they probably belong to the same general period of intrusion.

Some time after the intrusion of the diabase and before the great outpouring of the late Tertiary volcanics, which cap the hills of the outlying districts, the area was affected by important normal faulting which has profoundly influenced the topography and structure of the district.

The pre-Cambrian granite, the Paleozoic and Cretaceous sediments, the porphyry, and the diabase, have all been affected by the mineralizing solutions to a greater or less extent. The important ore-bodies of the early days of the district were found in the Paleozoic sediments, while at the present time it is the disseminated ore in the porphyry which is significant. In 1914, 97 per cent. of the ore mined by one of the larger companies was concentrating ore from the porphyry which averaged 2.8 per cent. copper.

[1a] Min. and Sci. Press Vol. 101, p. 777, 1910.

MINERALIZATION.

The term mineralization is somewhat indefinite and has been subject to varied usage. Probably the most logical conception of its meaning is the development of secondary minerals in which an important factor is the contribution of material from a source independent of the mineralized rocks. This does not come very far from limiting it to the work of heated solutions. In this paper the term mineralization will be used exclusively to refer to the vein filling, and hydrothermal alteration or other metasomatic changes accomplished by the heated solutions associated with the porphyry. Thus the rock alteration for which the porphyry intrusive is responsible is a phase of this mineralization. The distinction between the definition here chosen and another equally justified by usage which limits mineralization to the development of ore minerals, notably sulphides, should be kept in mind.

In connection with the study of the mineralization the chief problem involves the separation and classification of minerals according to their genetic occurrence, the recognition of the factors which have determined certain mineral associations, and the evaluation of these factors as to their influence on ore-deposition. The first distinction to be made is that between the primary rock-forming minerals and those developed by processes of secondary alteration. In further classifying the minerals of the second group it is first necessary to distinguish between differences due to the nature of the solutions acting, and those due to conditions of deposition or differences in the material acted on. In the classification according to the differences in the agencies of metamorphism, at least four types are to be considered, namely: contact alteration (pneumatolytic), hydrothermal alteration (sericitic and propylitic), weathering (in zone of oxidation), and the work of the solutions of secondary sulphide enrichment (meteoric solutions under deoxidizing conditions).

Minerals deposited in open spaces, chiefly as fissure filling are to be distinguished from those developed by alteration and replacement.

The different materials which influence the nature of the mineralization are the different rock formations of the district, namely, the igneous rock types, white porphyry, diorite porphyry, green mica rock, micropegmatite, diabase, and granite; and the sedimentary rock types, shale, limestone, and quartzite or sandstone.

DETAILED DESCRIPTIONS OF ROCK ALTERATION.

Granite Porphyry.—The fresh granite porphyry shows rather numerous white feldspar phenocrysts of various sizes (from 2¼ mm. down) in a fine grayish white groundmass. Tiny greenish spots are numerous, and small pyrite grains are not rare. There are usually some small quartz phenocrysts and occasional large bipyramidal ones (5 mm. across) which are the most characteristic feature of the rock. Weathered specimens are very similar to those to be described under monzonite porphyry.

Typically, the granite porphyry is intensely altered and is composed of sericite, quartz, and pyrite. With the pyrite are microscopic quantities of chalcopyrite. The sericite usually forms an extremely fine felt (fig. 2) though where associated with much secondary quartz some of it may be relatively coarse grained (fig. 1). The abundance of both the quartz and the pyrite varies greatly in different specimens. The pyrite occurs disseminated through the rock or in association with small veinlets of quartz which are of common occurrence. Pyrite individuals showing good crystal outlines are not rare. The quartz occurs chiefly in the groundmass and in the veinlets, while the feldspar phenocrysts are usually more or less delimited by areas of relatively pure sericite, though in the most thoroughly altered phase this distinction may be entirely lost.

In the thin sections of the freshest specimens feldspar phenocrysts, usually about 1 mm. in diameter or less, occupy about ⅙ of the area. These feldspars are chiefly albite. The large bipyramidal quartz phenocrysts as well as the smaller quartzes are of rare occurrence in comparison with the feldspar phenocrysts. Small biotite phenocrysts are also sparingly present. The groundmass is a fine micrographic aggregate of quartz and feldspar.

Sericite occurs sparingly in the groundmass and somewhat more abundantly in the feldspar phenocrysts. The biotites are either merely bleached or altered to chlorite.

The classification by Lindgren[2] as a granite porphyry is based on a partial analysis which gives: SiO_2, 69.13 per cent.; CaO, 0.22; Na_2O, 3.01; K_2O, 3.94, which is equivalent to 23.5 per cent. orthoclase molecule, 25.1 per cent. albite molecule, and 1.1 per cent. anorthite molecule.

Aside from those produced by weathering the typical secondary minerals of the granite porphyry are: sericite, chlorite, quartz, pyrite, chalcopyrite, chalcocite, and kaolin. The sericite, chlorite, quartz, and pyrite are typical of hydrothermal alteration, while the chalcocite and kaolin are ascribed to the processes of secondary enrichment.

The minerals of the zone of weathering to be discussed under monzonite porphyry, occur similarly in the granite porphyry.

Monzonite Porphyry.—In general the monzonite porphyry is only distinguished from the granite porphyry by the absence of the large bipyramidal quartz-phenocrysts and the scarcity of any quartz phenocrysts, though it sometimes has a greenish appearance as the dioritic type is approached.

The weathered porphyry shows yellow and red-brown colors with more or less black staining which make the outcrops picturesque elements of the scenery. The yellow-brown tinge distinguishes it from the granite and quartzite.

The sericitized phase of the monzonite porphyry is most typical and cannot be distinguished from the similarly altered granite porphyry (fig. 2).

In the thoroughly weathered specimens kaolin is usually abundant and sericite is less conspicuous under the microscope. Opaque limonite or hematite spots are of common occurrence. Pyrite may be removed leaving clean-cut cavities. Sometimes these are filled with opal which may have a limonite rim. Where chalcocite occurs it is usually associated with malachite and sometimes cuprite. The cuprite and malachite radiate outward from the chal-

[2] U. S. G. S. Prof. Paper 43, 1915

EXPLANATION TO PLATE XIX.

FIG. 1. Altered granite or monzonite porphyry. Sericite felt with conspicuous quartz. Crossed nicols. 30 diameters.

FIG. 2. Altered granite or monzonite porphyry. Typical sericite felt. Crossed nicols. 30 diameters.

FIG. 3. Green mica rock showing resemblance to sericite felt. Crossed nicols. 30 diameters.

FIG. 4. Green mica rock showing peculiar pyrite form and apatite rods. Ordinary light. 30 diameters.

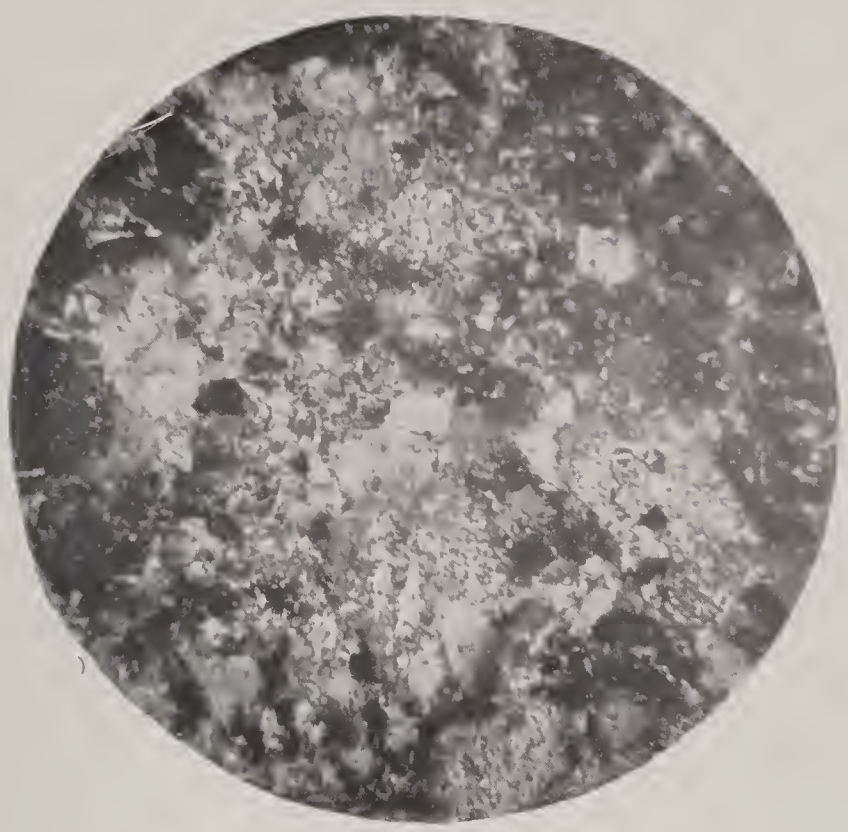

FIG. 1.

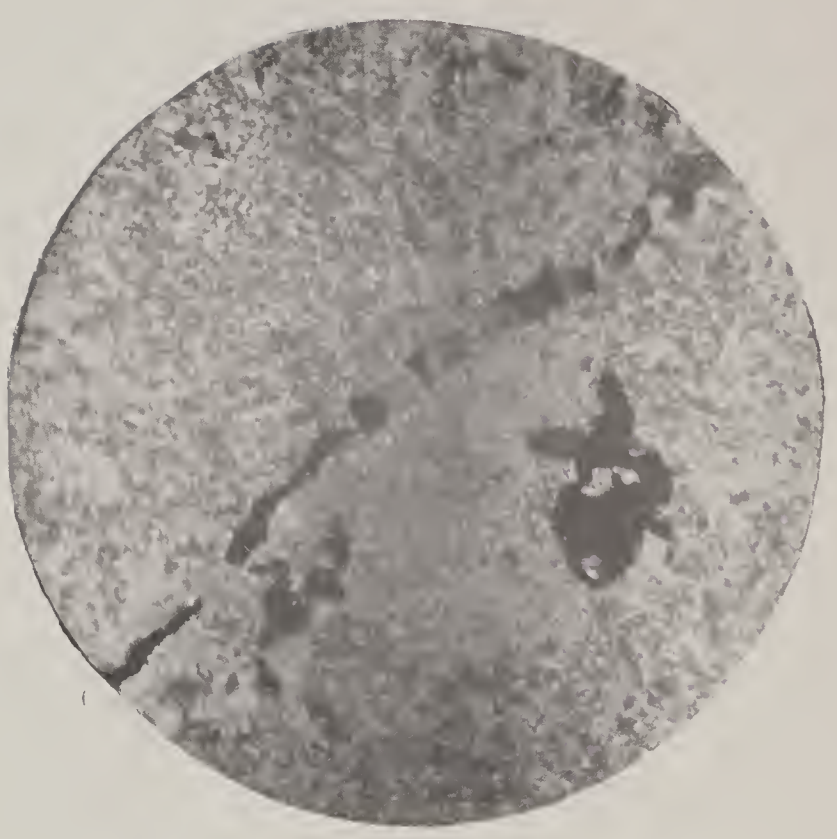

FIG. 2.

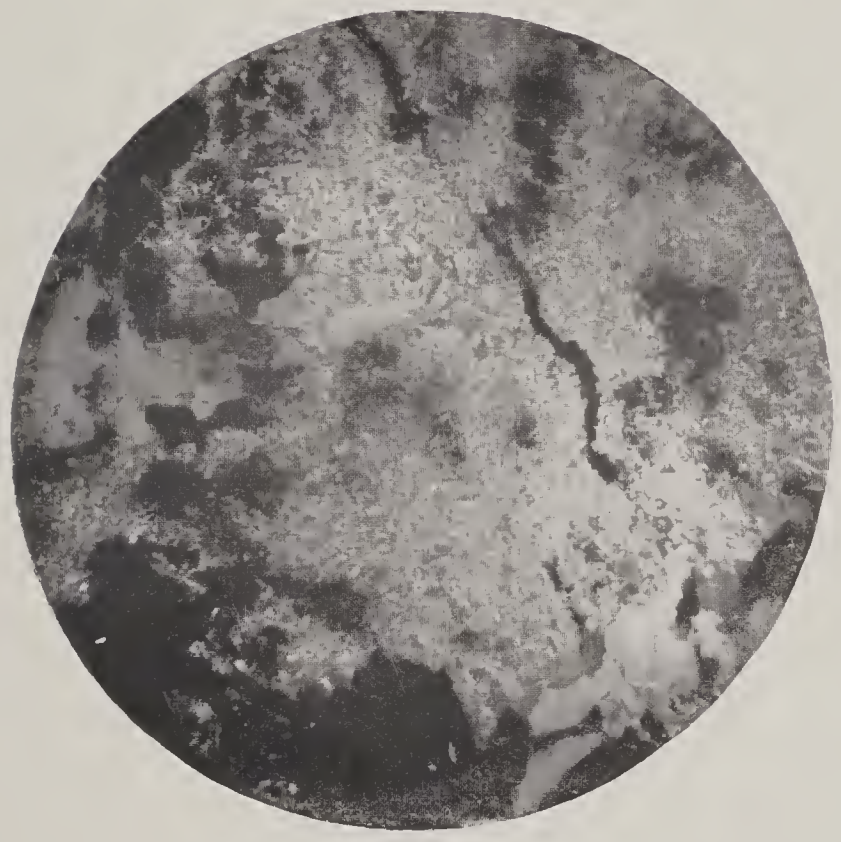

FIG. 3.

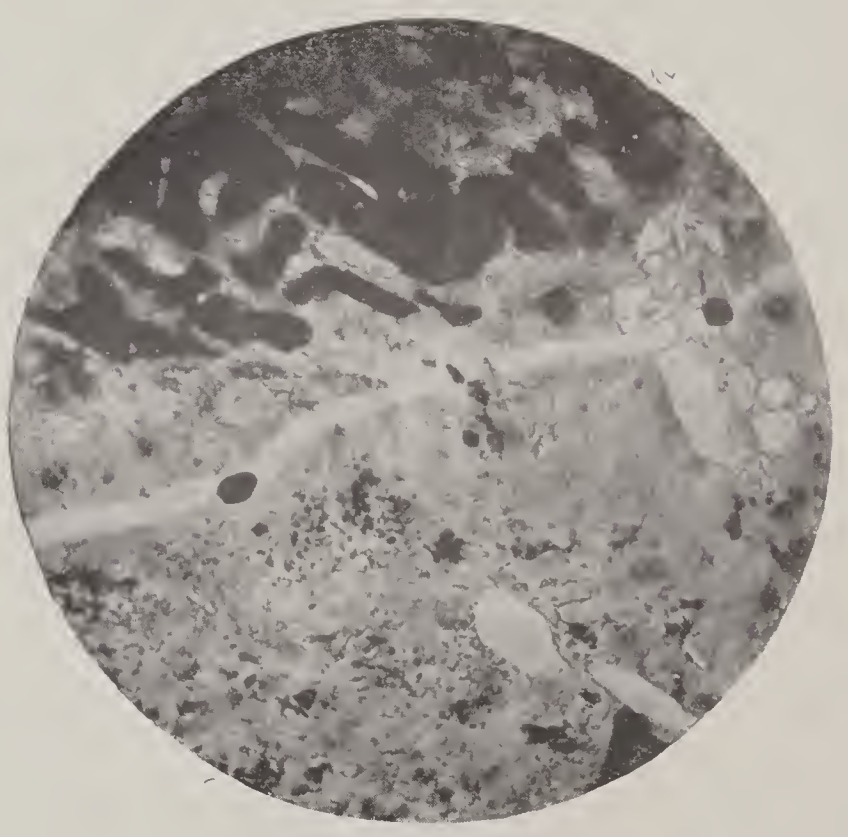

FIG. 4.

cocite from which they were formed and occupy a network of ramifying veinlets. Where both occur, the cuprite stays relatively near the chalcocite. Malachite may develop where other evidences of weathering are lacking. Chrysocolla is found further away from the surface than cuprite or the copper carbonates, and bunches of native copper are also found at relatively great depths though usually associated with more or less ferruginous oxide material.

A relatively fresh specimen of monzonite porphyry is described by Lindgren as follows:

> "Under the microscopic orthoclase, albite, and oligoclase, with an occasional crystal of labradorite are shown to be present. The plagioclase feldspars often show well developed zonal structure. The groundmass is coarsely microcrystalline, consisting of quartz and non-striated feldspar grains with occasional octahedrons of magnetite. Sericite is present in the feldspars while chlorite has formed from the biotite; a little secondary epidote also occurs."

Thus the fresh rock is a porphyry with phenocrysts of oligoclase, albite, orthoclase, biotite, and labradorite, in about the order of abundance named, in a micro-crystalline groundmass of quartz and feldspar.

Chemical analysis gives the following approximate mineral composition with the feldspar expressed molecularly:

PERCENTAGE OF MINERALS IN QUARTZ-MONZONITE-PORPHYRY FROM THE RYERSON MINE.[3]

Orthoclase molecule	16
Albite molecule	45
Anorthite molecule	10
Biotite	6
Quartz	22
Titanic iron ore	1
	100

From the thin section Lindgren concludes the most probable combination of the feldspars to give 38 per cent. albite and orthoclase, and 24 per cent. Ab_2An. Thus about 38 per cent. of the total feldspar is plagioclase.

[3] U. S. G. S. Prof. Paper 43.

The system proposed by Iddings and Pirsson[3] for classifying rocks of this type on the basis of the nature of their feldspar content is shown graphically in the accompanying table.

According to this classification a monzonite may contain from 37½ to 50 per cent. of the total feldspar in the plagioclase form. As the rock under consideration contains about 38 per cent. plagioclase, it is clearly a monzonite porphyry on this basis, though not far removed from the granitic type.

	% Alkali Feldspar.	% Plagioclase.
Granite	100	0
	87½	12½
	75	25
Monzonite	62½	37½
	50	50
Granodiorite	37½	62½
	25	75
Diorite	12½	87½
	0	100

The following secondary minerals are found in the monzonite and granite porphyries: sericite, quartz, pyrite, chalcopyrite, chlorite, chalcocite, kaolin, limonite, hematite, opal, cuprite, malachite, chrysocolla, and native copper. Sericite, quartz, chlorite, chalcopyrite, and pyrite are ascribed to hydrothermal alteration; chalcocite and kaolin to secondary enrichment: and kaolin with the remaining minerals to weathering.

Diorite Porphyry.—Very fresh specimens of the diorite porphyry are readily obtainable. Thus the opportunities for study of the unaltered rock is more favorable than in the case of the other phases of the porphyry of which even moderately fresh samples are obtained with difficulty.

The typical fresh diorite porphyry is a somewhat flinty gray rock, showing numerous small white plagioclase phenocrysts in a fine dark green groundmass. Both the depth of the green color and the abundance of the phenocrysts vary somewhat in different parts of the mass. Portions of the diorite porphyry show a scattering of long needle-like hornblendes, up to 1 cm. in length, which

[3] As stated by L. V. Pirsson.

are absent elsewhere. A scattering of tiny biotites is revealed by close scrutiny in nearly all the fresh material. In so far as this rock has been weathered or otherwise altered it tends to lose its green color.

The hand specimens show the original ferro-magnesian minerals of the diorite porphyry to have been hornblende and biotite. In thin section the hornblende is not easy to identify. It is probably represented by aggregates of fine secondary green hornblende and green biotite masses. The original biotites are usually in part preserved imbedded in secondary chorite. In many specimens the ferro-magnesian minerals are rather abundant. Pyrite is found occasionally in the ferro-magnesian areas. The plagioclase phenocrysts usually occupy about one half the area of the thin section and are of all sizes up to 4 mm. in diameter. They range from andesine to a rather basic labradorite, and the larger individuals are usually zonal. Epidote is a common alteration product and sometimes replaces entire phenocrysts. In some cases calcite and other carbonates may be abundant. Also flakes of colorless secondary mica are rather common. Tiny magnetites are usually present. Very rarely quartz phenocrysts are observed.

The groundmass varies from micro-granitic to trachytic in texture and probably contains some orthoclase as well as plagioclase. The same alteration products occur in the groundmass as in the phenocrysts, but in the groundmass they are often difficult to identify.

A partial analysis of the diorite porphyry from Prof. Paper 43 gives SiO_2 61.20; CaO, 5.11; Na_2O, 5.70; K_2O, 1.35, which is equivalent to 8.0 per cent. orthoclase molecule; 48.3 per cent. albite molecule; and 25.4 per cent. anorthite molecule. Thus it would appear that the plagioclase of the specimen analyzed was andesine.

The alteration which has affected the diorite results in the development of calcite, epidote, chlorite, hornblende, sericite, green biotite, pyrite, and possibly a very little secondary quartz. On the basis of these minerals and the field relations this alteration is classed as hydrothermal. It is possible that some of the most

calcitic phases are due to weathering, though as abundant calcite is in most cases intimately associated with the fine white mica, this is not believed to be the case.

Green Mica Rock.—The most characteristic, though probably not the most abundant phase of the green mica rock is uniformly fine grained and of a dull green color which appears black when moist. It contains abundant pyrite which occurs finely disseminated and in small veinlets. Though having a dull appearance and a rather soft consistency, the crystalline nature of the rock is indicated by numerous minute cleavage faces which show on a fresh fracture. Sometimes apatite crystals show as tiny white hairs which give the rock a diabasic appearance. The different variations of this rock comprise finely mottled types in which white chalky material is mixed with the green material in various proportions, and various mixtures with brown feldspar and siliceous material.

In the most typically developed phase this rock is made up of a fine felt of brownish green mica in which are imbedded numerous small rods of apatite, abundant pyrite, and more or less fine magnetite (fig. 3). The pyrite contains microscopic quantities of chalcopyrite. The apatite rods are usually about .1 mm. in diameter and from .2 to .4 mm. in length (fig. 4). The magnetite is usually difficult to detect in the thin section, but a small amount can be separated from the powdered rock with a magnet. In some specimens, however, it is conspicuous and abundant. Pyrite masses occupy a fifth or a sixth of the section area (figs. 3, 4, and 5). They are sometimes coated with a little chalcocite. In some parts of the rock more or less nearly colorless chlorite is associated with the green mica. Where the pyrite is most abundant there is often a little quartz.

The pyrite in some instances has a peculiar rounded branching form, somewhat similar to a portion of a micrographic intergrowth (fig. 4). Hematite often occurs with the magnetite, either massive or coating the other oxide. There are also gridiron forms suggesting the form of rutile called sagenite, but evi-

dently made up of plates rather than rods. These are believed to be hematite developed along cleavages of former pyroxenes. In the specimens similar gridirons of dark clayey material show 124° angles corresponding to basal hornblende sections. Definitely outlined areas, evidently preserving the form of previous amphiboles or pyroxenes, filled with clay, magnetite, pyrite, and hematite, occur with relative abundance.

The apatite is the oldest of the minerals now present in the rock. It usually has fractures filled with the green mica, and is often included by pyrite. In rare instances the pyrites are broken and contain green mica in the fractures, indicating at least some green mica younger than the pyrite.

The microscopic evidence shows that the original of the green mica rock was in its most extreme phase composed very largely of ferro-magnesian minerals, chiefly pyroxene or hornblende, with both probably represented, and sprinkled with abundant tiny apatites. It also contained more or less magnetite as an original constituent, and probably some feldspar. This extreme phase was evidently associated with gradations to the normal white porphyry.

The minerals of secondary occurrence in this rock are: green biotite, pyrite, chalcopyrite, chlorite, magnetite, hematite, quartz, chalcocite, kaolin.

With the exception of the chalcocite and kaolin, which are attributed to processes of secondary enrichment, the minerals are probably to be attributed to a single type of alteration. The intimate association of this rock with the micro-pegmatite suggests that this alteration may have contact metamorphic or pneumatolytic affinities. However the similarity of the green biotite to sericite and its association with minor amounts of chlorite is most suggestive of that type of alteration classed as hydrothermal.

Micro-pegmatite.—The micro-pegmatite is characterized by peculiar brown feldspar and inconspicuous gray quartz with abundant pyrite, some of which is in fine veins. The pyrite is less abundant than in the green mica rock. In some specimens the

EXPLANATION TO PLATE XX.

FIG. 5. Green mica rock showing abundant pyrite and apatite. Ordinary light. 30 diameters.

FIG. 6. Micropegmatite in contact with green mica rock. Crossed nicols. 30 diameters.

FIG. 7. Quartz-orthoclase micropegmatite. Crossed nicols. 30 diameters.

FIG. 8. Diabase showing typical ophitic texture. Crossed nicols. 30 diameters.

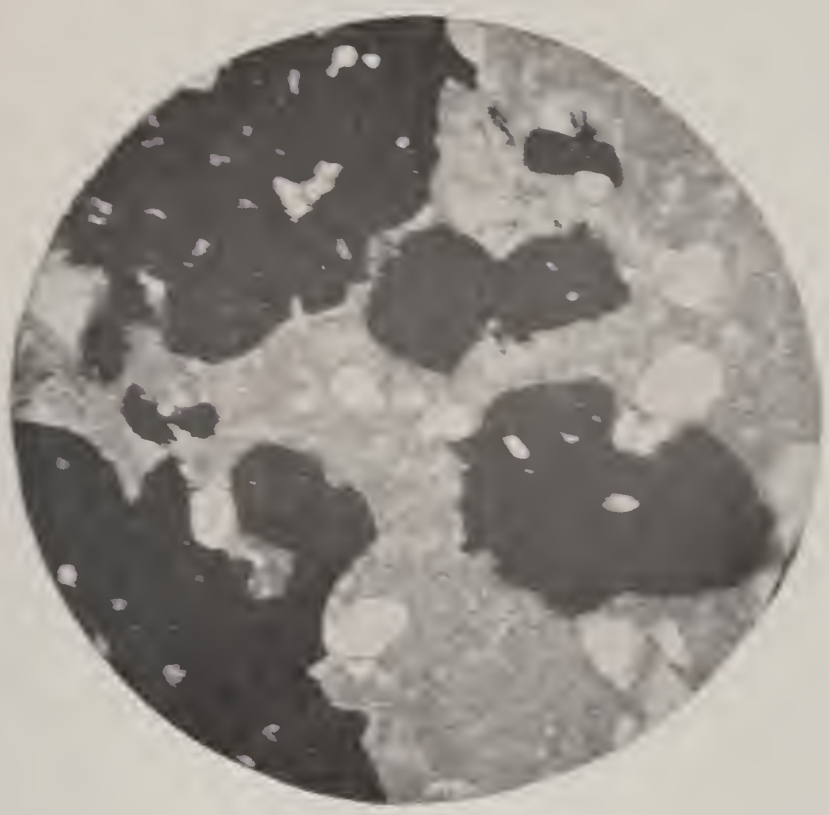

FIG. 5.

FIG. 6.

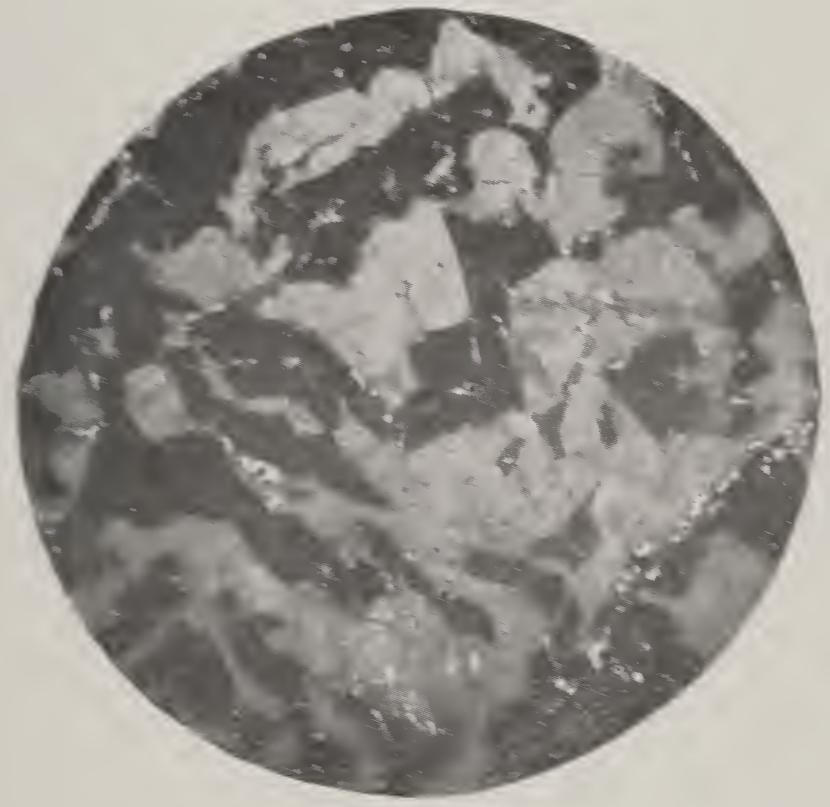

FIG. 7.

FIG. 8.

micro-pegmatitic structure can be recognized with a hand lens. The micro-pegmatite is quite generally associated with the green mica rock which it intrudes on a minute scale (fig. 6).

This rock when typically developed is very largely composed of a micrographic intergrowth of a rather irregular character composed of quartz and orthoclase feldspar (fig. 7). Sometimes the intergrowth is extremely coarse and sometimes very fine. A regular gradation from coarse to fine is not uncommon in a single individual. Large massive quartzes and orthoclases are also present. They sometimes occur in optical continuity with micrographic individuals.

Under the microscope the orthoclase where least altered has a dirty appearance like that produced by kaolinization and shows a distinct pale brown color when the thin section is observed with the unaided eye. Although the greater part of the orthoclase has been completely changed to sericite the preservation of considerable unsericitized feldspar in this rock in an area where no trace of original feldspar remains in the white porphyry suggests that the intrusion of the micro-pegmatite took place after the sericitization was partially complete. However, the more siliceous character of this rock may be in part responsible for the preservation of the orthoclase.

The alteration products found in the micro-pegmatite are sericite, quartz, and pyrite, and perhaps the indeterminate brown pigment material found in the least altered orthoclase. The sericite, quartz, and pyrite are the work of hydrothermal metamorphism. The brown pigment material may be a kaolinitic product, but it is believed unlikely that any meteoric agencies are responsible for its development.

Diabase.—The diabase is uniformly dark blue-gray to black in color. The texture ranges from that of a rather fine-grained variety to that of a variety which shows luster mottlings up to 5 or 6 mm. in diameter. The luster mottling is due to the interrupted cleavage faces of the individual poikilitic augites. In some of the coarser-grained types the plagioclase laths are difficultly visible. With alteration the diabase becomes lighter colored

and clayey in appearance. Where cupriferous it is full of irregular quartz stringers with more or less chalcopyrite.

Thin sections of this rock show a beautiful development of the diabasic or orphitic texture (fig. 8). Lath-like labradorite plagioclases form an interlacing mesh over the section like jackstraws. In the freshest specimens the greater part of the interstitial space is taken up by large nearly colorless augites which include a number of the feldspar laths. In most of the specimens the augite has entirely altered to a green hornblende which is full of tiny specks of magnetite. The hornblende has streaks of higher birefringence and greater pleochroism which may be due to inclusions of the brownish green biotite which occurs sparingly in the section as an alteration product. In addition to the augite and hornblende as interstitial filling, there are a good many aggregates of fine magnetite intergrown with talc and surrounded by serpentine. Sometimes they are formed of magnetite and serpentine alone. These magnetitic spots undoubtedly represent original olivines, now entirely altered (fig. 9). The serpentine manifests a tendency to migrate away from the olivine which furnished the material for its formation, and often fills fractures in the broken plagioclases. There is also more or less chloritic material developed in the ferro-magnesian areas, but it is not conspicuous.

There are occasional magnetite individuals of a different nature from those formed from the olivine. These are large and massive with clear-cut boundaries and appear to replace ferro-magnesian material and feldspar indiscriminately. This magnetite sometimes includes scraps of other secondary minerals, thus proving it a product of the mineralization, and not an original constituent of the rock. There is some fine white mica developed in the plagioclase, and scraps of calcite are occasionally observed.

In one section the alteration is chiefly to fibrous hornblende with spots of magnetite, and some epidote and a little quartz in the most distinct of the numerous tiny veins. The magnetite includes secondary hornblende. Hornblende-quartz veins cut the magnetite and the epidote-quartz veins. The epidote-quartz veins cut the hornblende veins more often than they are cut by

them. Thus three overlapping phases are shown: (1) Magnetite; (2) hornblende with a little quartz, and (3) epidote with a little quartz.

The minerals developed by processes of alteration in the diabase are green hornblende, fibrous hornblende, serpentine, magnetite, chlorite, talc, biotite, calcite, quartz, and epidote.

As the diabase is believed to be the youngest intrusive in the area, contact metamorphism can hardly be called on to explain the development of any of the secondary minerals listed above. Hydrothermal alteration is thus held responsible for the entire list.

Granite.—The typical pre-Cambrian granite is a moderately coarse-grained rock with decidedly pink feldspars, gray quartz, and occasional bluish black spots which resemble magnetite. Sometimes the feldspar lacks the pink color, and the quartz is less distinctly gray. In some localities fine-grained phases are encountered. A relatively local phase exhibits fresh black pyroxene with gray feldspar. In one locality the abundant ferromagnesian minerals make the rock resemble a gabbro.

In mineralized areas the granite often shows pyrite, or more rarely, chalcopyrite. It may become a uniform or blotchy deep red or a nondescript more or less chalky gray in color, and is sometimes so silicified that the feldspars are no longer distinguishable.

The characteristic reds and browns of the weathered granite are a picturesque feature of the landscape, where it is exposed.

The most usual type of the granite, which was called a magnetite granite in the field, in thin section shows large quartz and orthoclase individuals with coarse granitic texture. There are occasional areas where the quartz is associated with tiny magnetites, scraps of titanite and more or less leucoxene as well as considerable green biotite (fig. 10). Often the orthoclases are replaced by large microperthitic intergrowths of orthoclase and alkali-plagioclase. Small zircons are not uncommon. In most cases the feldspar is considerably kaolinized and only slightly sericitized. Near the porphyry contact the granite may be domi-

EXPLANATION TO PLATE XXI.

FIG. 9. Diabase showing spots of magnetite and talc representing former olivine. Ordinary light. 30 diameters.

FIG. 10. Magnetite, titanite, quartz, and green mica in area representing former ilmenite (?) Ordinary light. 30 diameters.

FIG. 11. Banded epidote-quartz rock. Ordinary light. 30 diameters.

FIG. 12. Sericitized quartzite. Crossed nicols. 30 diameters.

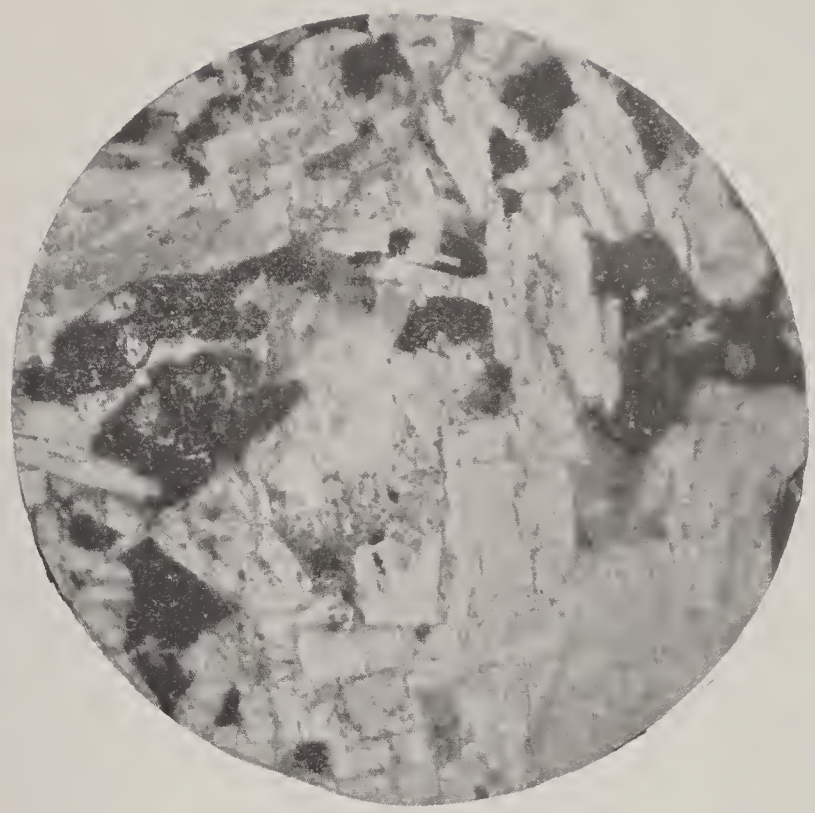

FIG. 9.

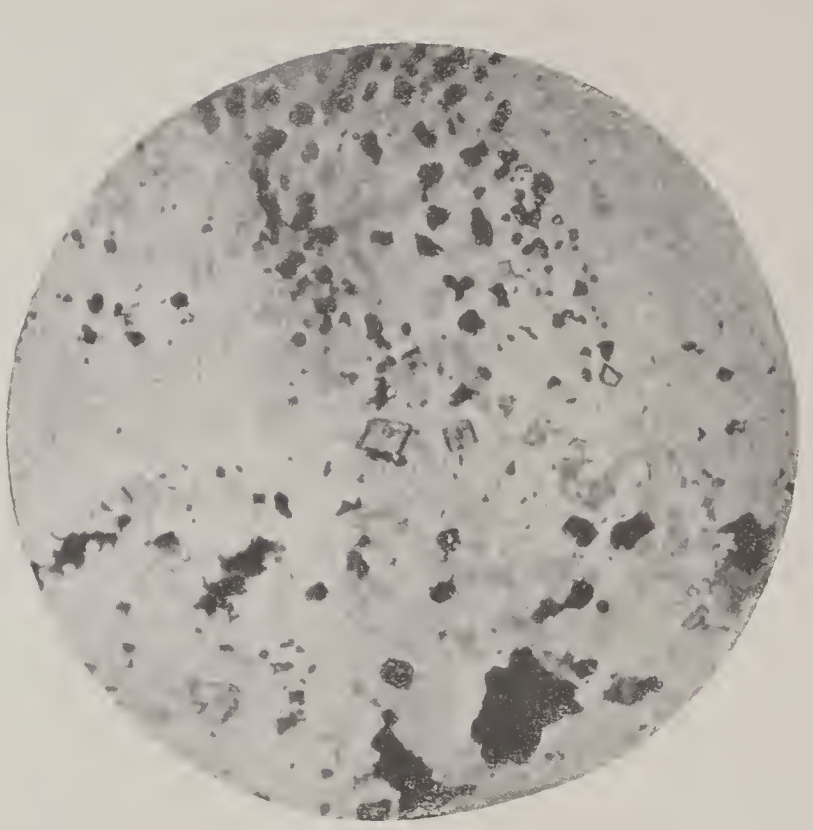

FIG. 10.

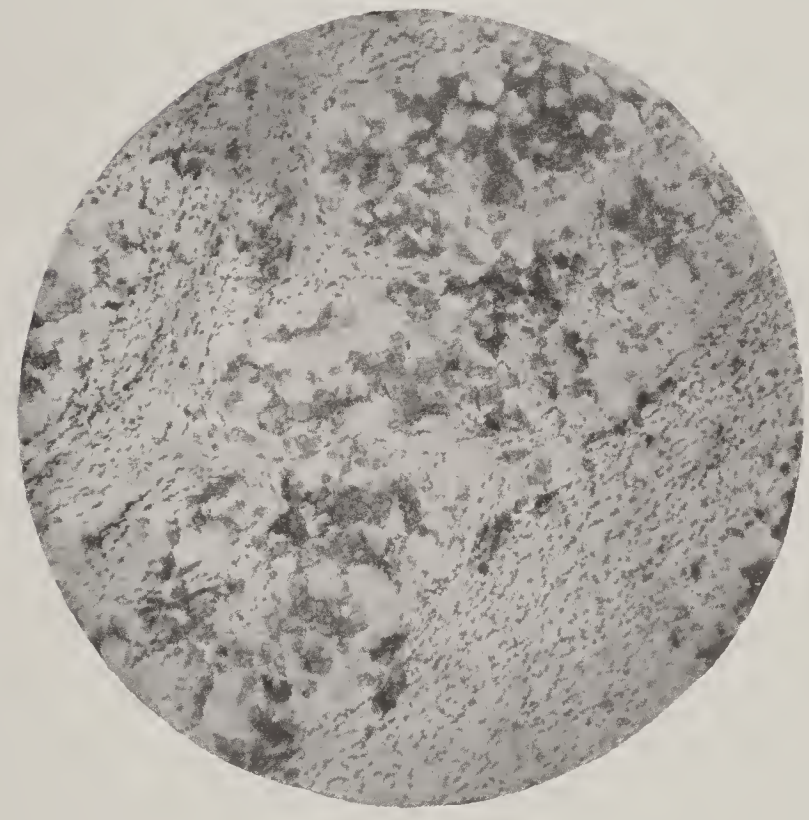

FIG. 11.

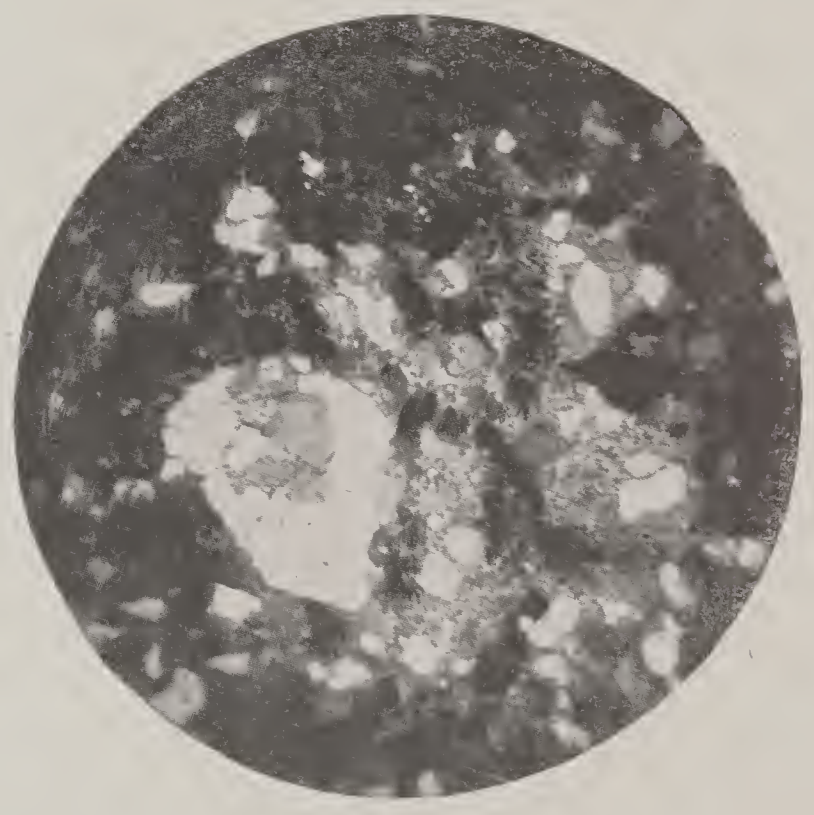

FIG. 12.

nantly sericitized or contain a great deal of secondary quartz. In this case more or less pyrite is usually present, and epidote and zoisite may occur in considerable abundance. Chalcocite and cuprite are sometimes found, and in a few cases the granite is mined as ore.

The gabbro-like phase has a rather typical coarse, granitic texture. The following minerals occur as primary constituents and in about the order of abundance named: alkali-plagioclase with fine albite twinning, orthoclase, nearly colorless augite, micrographic intergrowth of quartz and orthoclase, quartz, brown biotite, magnetite, and apatite.

Some of the orthoclase is quite thoroughly kaolinized. Elsewhere it contains both sericite and kaolin. There are thoroughly sericitized spots. The relatively fresh augite has a dirty alteration product along cleavage planes which makes it look like diallage. The augite is largely altered to hornblende which is itself locally altered to green biotite, sometimes to rutile, and possibly to magnetite.

The following minerals are developed in the granite by processes of alteration: kaolin, leucoxene, cuprite, chalcocite, sericite, pyrite, quartz, rutile, green mica, magnetite, hornblende, titanite (?) epidote, and zoisite. Four kinds of alteration are probably represented: first, weathering, producing kaolin, cuprite, and quartz; second, the work of meteoric waters in the zone of deoxidation, producing chalcocite, kaolin, and quartz; third, hydrothermal alteration, producing sericite, green mica, pyrite, magnetite, rutile, titanite, hornblende, leucoxene, and quartz; fourth, contact metamorphism producing epidote, zoisite, and perhaps hornblende.

Shale.—The most argillaceous rocks of the Devonian formation are very pure and uniform. The color ranges from gray to black, but in some cases becomes nearly white where blocks of shale are imbedded in the porphyry. Between the clay shale and material to be classed as shaly limestone, there are all gradations. The lower part of this formation is largely argillaceous limestone. In so far as these rocks are calcareous their alteration is similar

to that of the limestone. The most common alteration of the clay shales results in a paler-colored variety. They are largely composed of material which is microscopically indeterminate. Sometimes flinty epidotic rocks are formed. Epidote may occur disseminated throughout the rock or in tiny veinlets associated with quartz. Often minor amounts of tremolite or sericite occur, and it is probable that the white shales are largely sericite of submicroscopic grain. In these light-colored alteration products the coloring matter has become aggregated into tiny dark specks. The altered shales may contain occasional pyrite grains.

The Cretaceous shales are siliceous flinty rocks which often have very little shaly parting. They are uniformly dark green to black in color, or strikingly banded in gray and green. The banded shales are entirely very fine quartz and epidote; the coarser quartz bands with more epidote (fig. 11). The epidote makes up a fourth of the rock. The green or black shales are similar to the clay shales of the Devonian formation, but contain abundant fine angular sand grains and are more epidotic.

The alteration minerals of the shales are epidote, tremolite, sericite, pyrite, and quartz. The evidence as to the nature of the alteration producing these minerals is rather indeterminate. Epidote and tremolite are usually ascribed to contact alteration, while sericite is typical of hydrothermal. Epidote is also very characteristic of propylitization, but occurs under a wide range of conditions.

Limestone.—Fresh specimens of the limestone formations can readily be obtained within a short distance of the most intensely mineralized areas. The Cambro-Ordovician limestone varies from a fine-grained shaly gray rock to a crystalline, blue-gray variety of relative purity. In general it contains no fossils or other clues as to origin. Peculiar pebbly or concretionary forms are sometimes observed on the weathered surface.

The typical limestone of the Mississippian formation is a coarsely crystalline gray rock which often contains abundant crinoid stems and rarer coral or bryozoan remains. When freshly broken it emits a strong odor of hydrogen sulphide. This phase

is known as the gray cliff limestone because of its massive character which makes it the conspicuous cliff-forming member of the sedimentary series. Other subordinate varieties are coarsely crystalline dark blue limestone and various finer-grained less pure phases.

Chemical analyses show magnesia to occur rather abundantly in occasional beds. The quantity required to make the rock a dolomite is rarely approached in the Cambro-Ordovician limestone, but more frequently in the Mississippian formation.

Near the porphyry the limestone sometimes becomes pure white in color and more or less coarsely crystalline.

The most abundant end product of the alteration of the limestone is a massive vitreous rock composed entirely of brown garnet. Sometimes the crystal forms of the garnet show, and there is a little intergrown quartz. Some intermediate forms occur, and calcite, diopside, chalcopyrite, sphalerite, and garnet is not an extremely unusual association. Massive magnetite associated with more or less lime silicate material is another complete end product, while bright green rocks composed largely of epidote sometimes occur. More or less tremolite and serpentine may be associated with the epidote.

Very commonly the limestone is merely discolored, with numerous stringers and veinlets of pyrite. The rock may be of a somewhat bleached greenish color with irregular stripes and lines of darker color.

Tremolite is especially common in the shaly varieties. Antigorite and nearly colorless chlorite are of very general occurrence and may be uniformly disseminated or predominate in certain bands, while other bands are of coarsely crystalline calcite. Pyrite and magnetite sometimes occur in bunches. Hematite (specularite) is often associated with the magnetite and may occur in wonderful platy arborescent forms. The secondary quartz is almost always limited to tiny veinlets in association with pyrite or epidote. Antigorite also occurs characteristically in veinlets. Calcite occurs in veins and is sometimes associated with epidote.

Siderite sometimes occurs in massive form, and cerussite has been found in at least one locality.

Oxidized phases are most typical of the limestone which has been heavily pyritized, as the acid waters from the gossan penetrate the limestone with relative ease. Thus nearly massive yellowish phases and red-brown and buff more or less spongy material are not rare. This may contain pyrite preserved in the more siliceous portion, or may contain copper carbonates.

The most abundant development of the carbonate copper minerals, however, is usually in entirely decomposed, soft, iron-stained material. Here azurite occurs characteristically in nodules often with hollow centers lined with perfect crystals, malachite in more irregular forms, and rarer cuprite mixed through the spongy limonitic material. Often the oxides of manganese may give the decomposed limestone a nearly black color. Alunite occurs typically in large nodular masses in decomposed soft shaly limestone, close to a porphyry contact.

The secondary minerals developed in the limestones are garnet, epidote, magnetite, tremolite, antigorite, chlorite, specularite, diopside, chalcopyrite, pyrite, sphalerite, quartz, alunite, limonite, and other secondary oxides and carbonates. The oxides and carbonates are clearly due to weathering processes. The occurrence of the others in the specimens offers very little basis for their classification beyond the fact that garnet and magnetite are most often massive and most rarely found in veins. All these latter minerals, with the exception of serpentine, chlorite, and alunite, are usually classified as typical of contact metamorphism, while the serpentine and chlorite are believed to be of hydrothermal origin. The alunite is probably due to the work of secondary enrichment solutions.

Quartzite.—The Coronado quartzite varies from a coarse-grained, pebbly, well-cemented sandstone to an extremely fine-grained, vitreous quartzite. The finer-grained phases are not necessarily the most vitreous, though this is usually the case. The coarser-grained phases are most abundant, especially in the lower part of the formation. The coarser varieties in the lower horizons may be somewhat arkosic, otherwise, the rock is a very pure sandstone or quartzite, of a white or yellowish color.

Nearly all the quartzite contains enough pyrite so that surface weathering develops brilliant red and red-brown colors which make the outcrops of this formation picturesque features of the landscape.

The typical quartzite is composed of quartz grains of a rather uniform size, the larger ones well rounded and the smaller with a tendency to angularity. In the mineralized area the interstices are filled with sericite which ranges in abundance from a very small amount to a third or more of the rock (fig. 12). The actual size of the grains varies in different localities. The sericitic phases have a chalky appearance similar to that of the mineralized porphyry.

It is the very sericitic types which are best mineralized and seem to be most favorable to secondary enrichment. Disseminated pyrite, more or less heavily coated with chalcocite may occur abundantly. The pyrite is intergrown with microscopic amounts of chalcopyrite. Masses of mineralized quartzite are cut by occasional small quartz-pyrite or chalcedony pyrite veins.

The more vitreous material is usually made up of interlocking quartzes with only small amounts of sericite. Pyrite may occur imbedded in the quartz with clean-cut margins and good crystal form, but it is not, as a rule, very abundant in this phase.

The quartzite and quartzitic sandstone which occurs interstratified with the limestone is usually finer-grained than most of the Coronado formation. The arenaceous beds of the Cretaceous formation are pure fine-grained sandstone and not at all quartzitic. This sandstone is made up of uniformly fine, angular and sub-angular quartz grains, cemented by calcite and chalcedony.

The association of the most vitreous phase of the Coronado formation with the mineralized area suggests that much of the cementation has been due to the mineralizing solutions which were associated with the porphyry intrusive. It appears that in some cases the rock was silicified and in others sericitized.

The alteration which has affected the quartzite has resulted in the introduction of sericite, quartz, pyrite, chalcopyrite, chalcedony, and chalcocite, in a manner entirely comparable to the char-

acteristic alteration of the white porphyry. The chalcocite, and perhaps the chalcedony, is due to processes of secondary enrichment, while the other minerals are related to the hydrothermal alteration processes of the primary mineralization.

PROCESSES OF ALTERATION.

Contact Metamorphism.—Lindgren[4] distinguished between contact and hydrothermal metamorphism by limiting contact metamorphism to the vicinity of igneous contacts (in practice rather loosely), while hydrothermal is related to fissures which serve as trunk channels for the active thermal solutions.

At Morenci, and perhaps more notably elsewhere, as at Ouray,[5] the effects described as most typical of contact metamorphism sometimes occur at considerable distances from the igneous contacts and are related to fissures as well as to especially favorable sedimentary beds. In some instances effects like those of contact metamorphism are believed to have been produced by solutions which have altered the outer portion of the intrusive mass.[6] From this it is clear that solutions of some sort are instrumental in contact metamorphism.

It would appear to require a considerable stretching of the original conception of contact metamorphism to include all these instances. A conception of the areal relation sufficiently broad for this includes hydrothermal alteration with equal propriety.

Such a viewpoint is taken by Barrell,[7] who uses contact action as a general term which he divides into contact metamorphism and contact metasomatism, the former involving change of form alone, and the latter change of composition. Contact metasomatism is then divided into pneumatolytic alteration and hydrothermal alteration, depending on whether the solutions are acting at a temperature above or below the critical temperature of water (365° and 200 atmospheres). This division of metasomatism, as he notes, can only be used indirectly in practice. Hence for

[4] U. S. G. S. Prof. Paper 43, p. 124 (1905).
[5] Irving, J. D., U. S. G. S. Folio 153, 1907.
[6] Spurr, J. E., Econ. Geol., Vol. 7, No. 5, p. 485, 1912.
[7] Barrell, J., U. S. G. S. Prof. Paper 57, p. 116 (1907).

field use his distinction is based on the nature of the minerals formed.

Usage has refused to abide by this nice discrimination between metamorphism and metasomatism. Metamorphism is most often used as a general term for alterations (particularly of a constructive kind) which may or may not involve metasomatic action. This difference from present custom has resulted in considerable confusion in connection with the interpretation of Professor Barrell's results by later writers. He has been repeatedly quoted as supporting the view that material is never introduced during contact action, though the contrary is definitely indicated in the Marysville report.[8]

The term contact metamorphism is now usually applied to contact alteration producing heavy anhydrous silicate minerals, notably lime silicates, and corresponds to Barrell's pneumatolytic alteration. This restriction of a term which is logically a general one has come into vogue through the lack of a satisfactory designation for the more limited field.

A consideration of the recorded instances of contact metamorphism brings out in most striking manner the fact that the term is typically applied to the alteration of sedimentary rocks, most notably limestones. Lindgren[9] recognizes this fact in discussing contact metamorphism in his book on "Mineral Deposits." In a similar manner hydrothermal alteration is found to be characteristically associated with igneous rocks.

Here, then, is a rather fundamental distinction which appears to have escaped the recognition it deserves. This immediately brings up the question as to whether or not differences in the nature and condition of the metamorphic agents have not been unduly emphasized at the expense of this significant difference in nature of the material acted upon. To what extent is it possible that the same solutions may be responsible for contact metamorphism and for hydrothermal alteration, and to what extent is the common assumption that the latter is a lower temperature

[8] U. S. G. S. Prof. Paper 57, 1907.
[9] Lindgren, "Mineral Deposits," 1913, p. 664.

phase justified by unquestionable evidence? The prevalence of this opinion is, under the circumstances, a strong point in its favor. However, it is never amiss to inquire to what extent it is merely a matter of opinion.

The points upon which this conclusion rests are first: contact metamorphism has been assumed to occur only close to contacts and to take place early in the cycle of intrusion and mineralization, at a time when the intruded rocks are supposed to be at a maximum temperature; while hydrothermal alteration is known to take place chiefly after the outer portion of the intrusive mass has solidified. Second: minute structural relations indicate greater ability of the solutions of contact metamorphism to penetrate the rocks independently of fissuring than that possessed by the solutions of hydrothermal alteration, thus suggesting pneumatolytic affinities for contact metamorphism. Third: the minerals characteristic of contact metamorphism are in general of the dense anhydrous character believed to be typical of high temperatures, and in some specific cases have been determined to require high temperatures for their formation, while the more hydrous minerals most typical of hydrothermal alteration are generally considered as having lower formation temperatures.

The validity of the first assumption is entirely destroyed by the lack of close association of some contact metamorphic masses with igneous contacts and the discovery by Spurr[10] of an instance of contact metamorphic effects produced by solutions which passed through fissures in the already solidified outer shell of the intrusive mass supplying the material.

Aside from the distinction between vaporous and aqueous solutions it is known that the resistance to flow through capillary and sub-capillary openings decreases markedly with increase of temperature. Thus, in so far as contact alteration is more pervasive than hydrothermal, higher temperatures are indicated. Differences in the material acted on must be kept in mind in order to make this comparison a fair one. The greater penetrability of the sediments as opposed to igneous rocks may obviate the ne-

[10] Spurr, J. E., Econ. Geol., Vol. 7, No. 5, 485, 1912.

cessity for fracturing or the fracturing may be merely more difficult to detect. In the case of limestone the relatively greater solubility may dispense with the need for fracturing.

The third consideration is of great weight as contact metamorphism may almost be defined as the variety of alteration which produces heavy anhydrous minerals which require high temperatures for their formation. However it has not been conclusively proved that the minerals of hydrothermal alteration may not in some cases be formed at equally high temperatures, though it has been shown that in some cases they are probably formed at lower temperatures.

In view of the foregoing considerations contact metamorphism may be defined as a type of thermal metamorphism of sedimentary rocks, notably limestones, related areally to igneous contacts in a broad way and resulting in the development of heavy anhydrous silicates of the high temperature type, notably lime silicates. It is entirely possible that such metamorphism is in part pneumatolytic, and in part the work of aqueous solutions.

The minerals generally classed as typical of contact metamorphism are lime-garnets, epidote, wollastonite, diopside, amphibole, vesuvianite, magnetite, specularite, and pyrite, chiefly in limestones; and amphibole, epidote, feldspars, biotite, andalusite, staurolite, scapolite, and quartz, chiefly in shales.[11]

Of these the following are found in the metamorphosed sedimentary rocks at Morenci: andradite (calcium-iron garnet), epidote, diopside (rare), amphibole (tremolite), magnetite, specularite, and pyrite in the limestones, and amphibole (actinolite), epidote, and quartz in the shales. In addition: antigorite, common serpentine, and sericite occur in the limestones, while the quartzite (or sandstone) contains abundant sericite. The latter minerals are most typical of hydrothermal metamorphism. In the case of the "quartzite," which may have been originally an arkosic sandstone, the sericitization is to be classed as typically hydrothermal rather than contact metamorphic.

Evidence as to the paragenesis of the secondary minerals in

[11] Lindgren, W., "Mineral Deposits," p. 664, 1913.

the limestone is rather indeterminate. Epidote, tremolite, and serpentine are cut by later quartz-pyrite veins. Calcite, epidote, and chlorite occur associated in indefinite veins. Antigorite veins cut pyritized residuals of relatively fresh limestone. Serpentine occurs between garnet grains in a manner suggesting contemporaneous development. Thus epidote is to some extent younger than, as well as contemporaneous with the magnesian minerals, and there is a suggestion of contemporaneity of garnet and serpentine.

In Prof. Paper 43 Lindgren describes the alteration along a mineralized fissure as follows:

> "For a certain distance from the vein, ordinarily not more than a few inches or a few feet, the limestone is bleached and heavily impregnated with pyrite. A typical example is a dolomitic limestone from the Black Hawk No. 3 tunnel of the Shannon mine. The rock is grayish-green and partly altered containing besides much fine-grained calcite aggregates of colorless pyroxene and amphibole. This is cut by veinlets of coarse calcite, containing intergrown anhedrons of pyrite and magnetite, with a little chalcopyrite. Adjoining these veinlets and extending about half of their width are altered bands in which the limestone has been completely converted to prisms of colorless amphibole, probably tremolite. One or two of the same prisms are also contained in the veinlet itself, which apparently is produced by filling. Thus the metasomatic change exerted by the waters flowing through this fissure consists in the conversion of dolomitic limestone to tremolite."

Previous contact metamorphism has developed pyroxenes and amphibole and a vein including calcite, magnetite, and amphibole, etc., has developed amphiboles along its margin. Whether the alteration along this vein is classed as hydrothermal or contact metamorphism, it furnishes evidence of the close relationship between the two phases. As already brought out, the distinction between these two types of alteration, based on relation to fissuring, does not seem to be fundamental as even garnetization is seen to be related to fissuring in some instances.

The question of the importance of magmatic contribution in the development of the lime silicates characteristic of the contact metamorphism of limestones has been debated vigorously within

the last few years. Instances have been brought forward which conclusively prove the truth to lie with the upholders of one side or the other, indiscriminately.[12] The conclusion is unavoidable that in specific instances both extremes are represented. A consideration of those occurrences most nearly corresponding to that at Morenci strongly favors the belief that the great lime-silicate masses of these contact zones have been developed with the aid of enormous accessions of material furnished by the intrusive mass.[13]

At Morenci the most conspicuous and abundant lime-silicate rock is composed of massive calcium-iron garnet.

The four possibilities in a given instance of contact metamorphism are (1) that the material present in the original rock may remain of the same chemical composition, (2) that various amounts of certain constituents may be eliminated, (3) that material may be added, and (4) that certain constituents may be removed, wholly or in part, and other constituents may be introduced. Probably examples of each of these cases exist somewhere.

In the passing from a relatively pure limestone to a nearly pure garnet rock, only two of these possibilities are under consideration. Either the change has taken place entirely through the elimination of material or some material has been added and some subtracted. The garnet rock is about two thirds silica and iron oxide by weight, while a series of analyses of the limestone from the Detroit Copper Co.'s quarry in the member of the Modoc formation which is most subject to replacement by garnet rock, shows the material other than calcium and magnesium carbonates to average less than 3 per cent. It would take between 20 and 30 cubic feet of limestone to make one cubic foot of garnet rock if the change were produced entirely by the elimination of material.

If only CO_2 were eliminated and other material added, a volume increase of about one half would be required.

The structural relations at Morenci indicate beyond a reason-

[12] Leith, C. K., and Mead, W. J., "Metamorphic Geology," p. 140, 1915.
[13] Lindgren, W., "Mineral Deposits," 667, 1914.

able doubt that there has been no such great contraction of volume as that required by the adherents of the theory that little or no material was added to the original calcareous rocks. As has been emphasized before, the intrusive contacts are everywhere sharp and angular with many engulfed blocks and no crumpling of the sedimentary beds. The bedding of the limestone is in many places clearly preserved in the structure of the secondary silicate rock. Individual beds which have proved most favorable to alteration lie between other beds whose unaltered character allows no uncertainty as to their undeformed condition. Also in passing along the bed containing garnet rock to fresh limestone, no evidence of vertical settling can be found. Similar considerations eliminate the possibility of marked increase of volume. Thus it seems in this case to be indisputable that the development of the enormous masses of garnet rock which exist at Morenci is the result of a volume for volume replacement such as has been emphasized again and again by Lindgren.

Another corroborative fact is found in the occurrence of lime-silicate material identical with that of the replaced limestone as undoubted fissure filling.

Lindgren[14] computes that since the change has taken place at constant volume for every cubic foot affected approximately 29 pounds of CaO and 74 pounds of CO_2 must have been carried away, and 83 pounds SiO_2 and 74 pounds Fe_2O_3 have been added.

It is in connection with these lime-silicate contact metamorphic rocks that the phenomenon of replacement is most characteristically developed.

In his study of metasomatic processes Lindgren[15] brings out the fact that the substitution of one molecule for another is not the usual governing principle in replacement as was formerly believed to be the case. In opposition to the principle of molecule for molecule replacement, he established the principle of volume-for-volume replacement as being of most general applicability. The emphasis laid on this latter principle carries with it

[14] Lindgren, W., U. S. G. S. Prof. Paper 43, p. 154, 1905.
[15] Lindgren, W., Econ. Geol., Vol. 7, No. 6, pp. 521–536, 1912.

the implication that it is based on some physical-chemical law such as that believed to govern the former. In all probability this is not the case.

From a physical-chemical point of view we may look upon any mineralizing solution as part of a system which is endeavoring to maintain equilibrium under changing conditions. The possibilities of variation of the external conditions are so great that it may be assumed that equilibrium is almost never maintained. The changes of temperature and pressure, and of the solid materials in contact with a given portion of the solution due to flow through the vein channels, and the change of the composition of the solutions due to admixture of different solutions by the intersecting of lines of flow, will in general maintain the unbalanced condition of the system. Similar considerations apply to pneumatolytic emanations traversing sub-capillary passages. In the continuous endeavor to reach equilibrium, the solutions may be depositing one or more substances or dissolving one or more substances, or depositing some and dissolving some at any given point. It is in the last instance that we have the phenomenon of replacement.

As a general physical-chemical proposition there is no constant quantitative relation between the material deposited and the material taken into solution. In discussing this relation volumetrically there are three possibilities to be considered; namely, more material may be deposited, or more dissolved, or equal volumes may be deposited and dissolved. Aside from the question of available space, the possibility of the third condition being fulfilled, rather than another, is as the magnitude of a point compared with a straight line of indefinite extent. However, in replacement the available space imposes a limit on deposition. The tendency to deposit more than is dissolved can only result in a volume-for-volume exchange. That the other possibility, of less deposition than solution is sometimes realized, is an observed fact, and its rarity in replacement bodies (in so far as it is of uncommon occurrence) may be explained by the fact that solutions tend to move in the direction of decreasing temperature and pressure,

and decreasing temperature and pressure in general promotes deposition rather than solution. The increased solubility of the material being replaced, due to the pressure exerted by the crystal growth of the material being deposited, may aid volume-for-volume replacement.

Here then we have the "Law of Equal Volumes" as established by Lindgren as fundamental in the formation of replacement deposits. According to the foregoing conception it is not a melocular or a volumetric equivalence which is most fundamental in replacement—it is the continued endeavor to reach equilibrium of a complex physical-chemical system whose unbalanced state is being more or less continuously maintained. That juvenile solutions usually have a greater tendency to deposit than to dissolve, due to fall of temperature and pressure, is sufficient explanation of the fact that the volume-for-volume relationship is commonly exhibited in replacement.

In the light of the foregoing conception of replacement it seems probable that pressure conditions tending to close up openings as fast as they were formed would hinder the development of volume-for-volume replacement such as exhibited at Morenci. In that case the occurrence of the replacement is evidence of the absence of great pressure.

Hydrothermal Alteration (Propylitization).—Kemp[16] says in regard to the original use of the term propylite:

> "It was created for a series of rather coarsely crystalline or granitoid andesites, that are of early Tertiary age, and often have the dark silicates altered to secondary minerals. The name means 'before the gates,' and the significance was that coming just before the geological time of the true volcanics, yet resembling them, they deserved this distinction. It is now obsolete, and reasons for its special existence were long ago exploded, but having been employed on the Comstock lode it has passed into western usage."

Becker[17] in connection with his work on the Comstock lode showed that the so-called propylites were highly altered andesites and basalts, hence the term propylitic alteration. Since then the

[16] Kemp, J. F., "Handbook of Igneous Rocks," p. 41, 1899.
[17] Becker, G. F., U. S. G. S. Mono. B, p. 33, etc., 1862.

term has been used rather indiscriminately. Probably the definition best in accord with usage is any alteration of igneous rocks in which hydrous magnesian alteration products are important and are associated with more or less epidote and carbonates.[18]

The above definition justifies the application of the term propylitization to the alteration which has affected the diabase at Morenci. This alteration is characterized by the development of serpentine, hornblende, tremolite, epidote, magnetite, calcite, chlorite, biotite, talc, and sericite. Some of these minerals suggest higher temperature and closer affinity to contact metamorphism than in the case of alteration where chlorite predominates.

In the Lake Superior region the Kewatin greenstones in general are abundantly chloritized, while hornblendic phases occur locally where there is a fairly close association with the later intrusives.

Without comparative analyses it is impossible to make any accurate quantitative determination of the change in chemical composition produced by the alteration of the diabase. However, it is probable that the change has not been extreme, as the secondary minerals appear to be very largely related to the composition of the primary minerals.

A general study of the relationship between propylitization and sericitization indicates that the chemical changes in this case are probably very similar to those which have affected the porphyry. Fragments of diabasic breccia along quartz chalcopyrite veins are entirely sericitized.

(*Sericitization*).—Sericitization is the almost universal expression of the hydrothermal alteration of acidic igneous rocks. Thus it is a common feature of many of the mining camps of the western United States. A set of specimens of sericitized porphyry from the various western mining camps would not differ greatly from a rock heap from any particular one.

The granite and monzonite porphyries at Morenci have their feldspathic and ferro-magnesian constituents entirely changed to sericite over large areas where the mineralization is most intense.

[18] Compare Lindgren, W., "Mineral Deposits," p. 446, 1913.

This development of sericite is characteristically associated with more or less pyrite in disseminated grains and in veins with quartz. More or less secondary quartz may also be added to the rock, though in general this is not conspicuous, and in some cases original quartz has been removed.

In the less extreme phase of this alteration the feldspar may be only partially changed to sericite, and the biotites merely bleached or altered to chlorite.

The less quartzitic portions of the large engulfed blocks of the Coronado formation which occur abundantly along the border of the porphyry mass in the town of Morenci are sericitized in a manner entirely comparable to that in which the adjoining porphyry is affected. Sometimes as much as a third of the rock is composed of sericite, though no evidence has been found indicating the replacement of the original quartz grains by sericite.

The diorite porphyry is much less widely or intensely altered than the more acidic phases of the porphyry mass. All in all, the alteration of this rock is to be called sericitization only by courtesy. Just as the diorite porphyry is, in a measure, a type intermediate between the granite-monzonite porphyry and the diabase, so, aside from the question of intensity, the alteration of the diorite porphyry is, in a measure, intermediate between the sericitization of the one and the propylitization of the other.

Sericite, calcite and epidote occur more or less abundantly through the rock. Green biotite, secondary hornblende, tremolite, chlorite, and rare pyrite represent the former hornblendes. The original biotites are bleached and changed to chlorite around the margins.

A comparison of the analyses of fresh and altered specimens of the monzonite porphyry given in Professor Paper 43 shows the chemical changes due to sericitization. By means of a computation to introduce a corrective factor for any change of specific gravity involved, the material actually introduced or removed is expressed in terms of per cent. of the original rock mass, and shown graphically on Plate VI. (broken line number 4). This plate is explained further on.

(*Biotitization*).—It is believed that the occurrence of green biotite in a similar manner to that of sericite has not been previously described. The conditions under which it has here been formed are somewhat problematical. The analogous occurrence of this secondary green biotite and the sericite indicates hydrothermal development, while the intimate association with the younger micropegmatite intrusive suggests pneumatolytic associations.

This alteration most needs be studied entirely from the point of view of the completely altered rock, as no unaltered equivalent has been found. The green mica rock consists very largely of a finely divided felt of brownish-green biotite which is very similar to the sericite felt developed in the porphyry. Scattered through this felt are numerous small apatites and abundant pyrite masses. The apatite is clearly the oldest mineral present. Sometimes there is also a little quartz with the pyrite, and a small quantity of colorless chlorite is intergrown with the biotite felt. Magnetite and specularite are rarely observed in thin section, and fine magnetite is nearly always detectable in the powdered rock.

The following chemical analysis (I.) was made of the green biotite from this rock. The separation of the mica was accomplished with a heavy solution, and an examination of the sample with a magnifying glass showed it to be of a high degree of purity, although extremely minute traces of pyrite escaped elimination.

Column II. gives an average analysis for the Morenci sericite

	I.	II.	III.
SiO_2	45.54	46.70	− 1.16
Al_2O_3	18.98	35.50	−16.62
Fe_2O_3	.52	1.12	.60
FeO	7.17	.17	7.00
MgO	10.79	....	10.79
CaO	2.36	....	2.36
Na_2O	1.19	.36	.83
K_2O	7.67	11.55	− 3.88
H_2O	1.80	5.00	− 3.20
H_2O	.07		
F	0.00		
MnO	1.01		1.01
TiO_2	3.01		3.01
	100.11	100.00	

as deduced by Lindgren[19] from the rock analyses. Column III. is the result obtained by subtracting the sericite from the biotite.

The biotite seems to be a rather average biotite in most respects. The amount of ferrous iron is trifle unusual, and the lime is higher than is commonly found. The contrast between this normal biotite and the markedly hydrous white mica which is typical of the sericitization suggests that a temperature difference in addition to difference in the material acted on may be required to explain the differences in the two resulting alterations. The presence of magnetite and specularite point in the same direction as well as the somewhat coarser habit of the green mica as opposed to the sericite. The sericite also shows a tendency to develop a coarser texture in the vicinity of the biotite. The biotite occurs in small veins much more abundantly than sericite ever does. There is then at least a strong suggestion of higher temperature conditions incident to the formation of the green biotite than those under which the sericite normally develops. These are of course readily explained by the presence of the micropegmatite.

INTERRELATION OF PROCESSES OF MINERALIZATION.

Sericitization and Propylitization.—In the outlying portions of the district where porphyry and diabase occur together, the opportunity for the study and comparison of the effects of mineralizing solutions on the two rocks is particularly good. The relation between the sericitic and propylitic types of hydrothermal alteration is a question which has been discussed by various students of the rock alteration accomplished by mineralizing solutions.

The sericitic alteration which is universal in the mineralized portions of the porphyry changes a rock consisting of plagioclase, quartz, and occasional biotite phenocrysts, and fine-grained granitic groundmass of quartz, orthoclase, and alkalic plagioclase to a finely felted aggregate of quartz and sericite. The outlines of the phenocrysts are preserved to a greater or less degree by areas

[19] U. S. G. S. Prof. Paper 43, p. 170.

of relatively pure sericite. The original quartz of the rock usually remains unaltered, and considerable secondary quartz may be introduced. This is in general inconspicuous. In the highly sericitized rock no trace of biotite remains. Less thoroughly sericitized specimens in which the plagioclase phenocrysts are not sericitized beyond recognition always show the biotite bleached or more or less completely altered to chlorite.

This development of chlorite is clearly related to the propylitic type of alteration, and occurs here as a less intense phase of sericitization.

The diabase dike rocks, the alteration of which is believed to be correctly classified as of the propylitic type, were originally composed largely of labradorite and augite. In the more altered rocks the labradorite is not entirely gone, though it is somewhat sericitized and encroached on by the serpentine resulting from the alteration of the augite. The augite is changed to hornblende or more completely altered to actinolite and serpentine.

The sericitic alteration of the porphyry dikes adjacent to the diabase dikes is of less intense character corresponding to that observed in the outskirts of the mineralized area in the main porphyry mass, where the biotites are still recognizable.

Study of analyses illustrating rock alteration of these types in other localities brings out more strongly the relation between the sericitic and propylitic changes suggested at Morenci.

Of all the available pairs of analyses illustrating rock alteration with which the specific gravity of the fresh and unaltered rocks are given, thus making possible the quantitative computation of chemical changes,[20] the group showing a gain in potassa includes all those representing sericitic and propylitic alteration. Taken as a class there are no uniform differences between the sericitic and propylitic types. The chemical changes common to both these types of alteration are quite uniform. The circular diagram (fig. 30) showing graphically the losses and gains involved in each case brings out this fact strikingly. Marked gains in potassa and combined water, and a marked loss of soda, a marked

[20] Method used by Ransome in U. S. G. S. Prof. Paper 75, 1911.

loss in lime, and a somewhat smaller, though equally constant loss of magnesia, are shown.

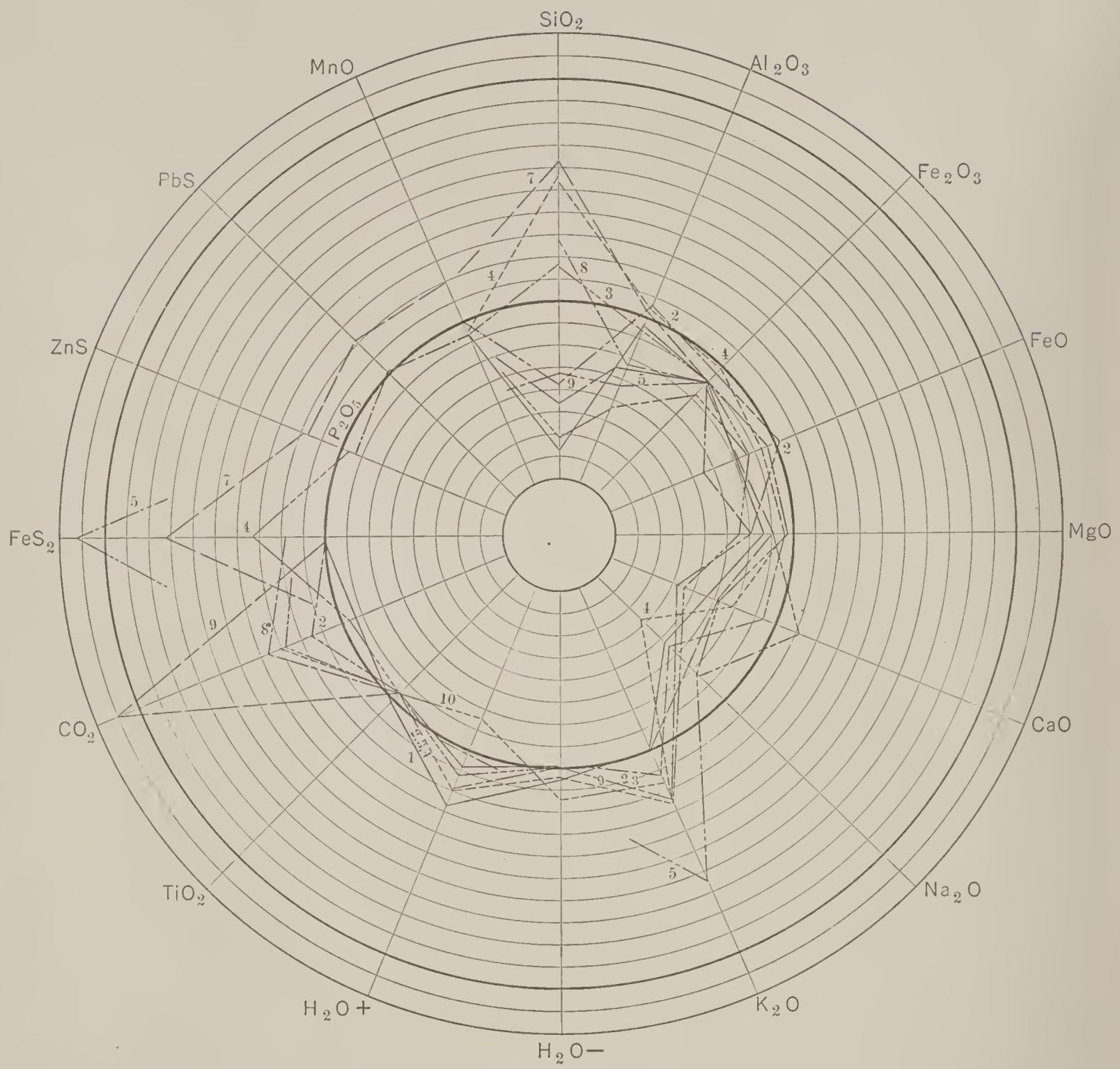

FIG. 30. Sericitization and Propylitization. (1) San Francisco Monzonite, sericitic (?); (2) San Francisco Monzonite, sericitic; (3) Hailey, Idaho Diorite, sericitic and propylitic; (4) Morenci Granite Porphyry or Monzonite, sericitic and propylitic; (5) Leadville White Porphyry, sericitic and propylitic; (7) Rimini Monzonite, sericite tourmaline; (8) Willow Creek, Idaho, Grano-Diorite, sericitic and propylitic; (9) British Columbia Diorite, propylitic; (10) Hauraki, New Zealand, Andesite, propylitic.

The iron oxides also show rather constant loss aside from that

introduced with the pyrite which is usually an accompaniment of this type of alteration. The introduction of CO_2 in greater or less amount also appears to be the rule, though probably this is more true of propylitization than sericitization. The diagram also indicates that the changes in silica and alumina are not essential features of this alteration, as sometimes gains are shown and sometimes losses. The pairs of analyses plotted are about equally divided between those which show a loss of silica and a gain of silica.

In the utilization of pairs of rock analyses to determine material contributed and abstracted by mineralizing solutions, it is necessary to know the specific gravities of the fresh and altered rocks represented by the analyses, and the volume change. It has been found, however, that as a rule there is practically no volume change. Where there has been volume change it should be possible to recognize it in the structural features or the development of porosity. Assuming, then, two analyses, one representing an unaltered rock, and the other a rock which has been subjected to action of mineralizing solutions, with the specific gravity of each determined and a reasonable probability that no volume change has taken place, it is possible to determine quantitatively the chemical changes which have taken place with a fair degree of accuracy. In making these computations the two analyses are first recalculated to total exactly 100 per cent. Each analysis is then divided through by its specific gravity, giving grams of each constituent in 100 c.c. of each rock. Comparison of these two columns will show the quantitative changes which have taken place. If the one representing the fresh rock be subtracted from that representing the altered rock, the positive values represent material added by the mineralizing solutions, and the negative values represent material abstracted, in terms of grams per 100 c.c. of rock. Dividing this column through by the specific gravity of the fresh rock expresses the same quantities in terms of grams per 100 grams of fresh rock. It is these values which are used in plotting the diagrams showing graphically the work of the mineralizing solutions. The possibilities of error in such

determinations lie in (1) the difficulty of securing accurate determinations of specific gravity, as the specific gravity, to be accurate for this work, should include such porosity as may exist in either of the rocks under comparison, and (2) the necessary assumption that there has been no volume change, which may be more or less well founded. However, it is reasonably certain that any inaccuracy in the result attained in this way will not be sufficient to invalidate the conclusions drawn from them in connection with this discussion.

In the diagram used for the graphic presentation of these results the heavy circle represents the composition of the unaltered rock while radial distances measured by the concentric circles represent percentages. The losses are measured from the heavy circle toward the center, and the gains are measured outward. A separate radial line or spoke on the wheel is used for each constituent, and the points showing the individual losses or gains are joined by straight lines to emphasize their position. Thus in the plate each broken line threading the spokes of the wheel represents an instance of rock alteration.

This diagram brings out quite strongly the intimate relationship between the solutions producing alteration of the sericitic and the propylitic types respectively. If the solutions are similar the marked difference in the alteration products ascribed to these processes must be due to the different composition of the material acted on.

It has been pointed out that alteration of the propylitic type is observed at Morenci in the ferro-magnesian minerals of the less intensely altered porphyry, and succumbs entirely to the sericitic alteration in the more intensely altered phases. Similar cases of propylitic changes developing at an early stage in the rock alteration are observed at Butte[21] and elsewhere. The chemical change required to eliminate the chlorite developed by sericitization is obviously the removal of magnesia which is apparently a universal feature of both sericitic and propylitic alteration. The

[21] W. J. Mead, personal communication; also various published descriptions.

more intense and thorough the alteration, the more magnesia will be eliminated, and the more the alteration will tend to become sericitic rather than chloritic or propylitic. Where the original supply of magnesia is somewhat limited, intense alteration easily eliminates the chlorite; while in the ferro-magnesian rocks the sericitic stage is seldom reached.

Contact Alteration and Hydrothermal Alteration.—According to Van Hise's[22] classification of metamorphic changes those which involve the breaking down of rock minerals into simpler forms are classed as katamorphic, while those involving the production of complex forms are called anamorphic. The process of weathering produces the type examples of katamorphic changes, and this process involves oxidation, hydration, and carbonation, while the constructive anamorphic changes are deoxidation, dehydration, and decarbonation, thus further distinguishing between the two types of metamorphism. Contact alteration is anamorphic in its nature.

The changes produced by hydrothermal alteration are typically katamorphic, though to a much lesser degree than in the case of weathering. The minerals produced by hydrothermal alteration are in general somewhat more hydrous and include more carbonates than the igneous rock minerals which they replace, and they are probably somewhat simpler in chemical structure. Thus hydrothermal alteration is intermediate between weathering and alteration of the type which develops complex anhydrous silicates, and would be expected to grade into these other types at either extreme. The change from highly crystalline anhydrous minerals to the simpler and more hydrous compounds developed by the process of weathering and sedimentation and back again to the more complex form by anamorphic process has been termed the metamorphic cycle.[23]

The close association in the metamorphic cycle of the minerals typically developed by contact metamorphism and original igneous rock minerals accounts for the slight effect of contact metamorphism on fresh igneous rocks; while the katamorphosed na-

[22] U. S. G. S. Mon. 47, 1904.

[23] Leith, C. K., *Journal of Geology,* Vol. 15, p. 303, 1907.

ture of sedimentary material renders it particularly susceptible to contact alteration. On the other hand hydrothermal alteration which is, in a measure, katamorphic in its nature affects igneous rocks more conspicuously than sedimentary rocks. Further it is to be expected that hydrothermally altered igneous rocks are more susceptible to contact alteration and contact altered sediments to hydrothermal alteration than the original rocks.

From the foregoing conception it would appear that there is a very fundamental distinction between contact metamorphism and hydrothermal metamorphism indicated by the nature of the rocks chiefly affected by each type of alteration. The difficulty often experienced in discriminating between contact and hydrothermal alteration suspected of occurring together in the same rock indicates the absence of any break between the two phases and further that the change from solutions producing anamorphic effects to those producing katamorphic effects or vice versa, may be a gradual one. The distinction, based on the material affected is important.

In the most conspicuous and extreme variety of contact metamorphism, the development of massive garnet, great quantities of silica and iron are supplied by the mineralizing solutions, and lime and magnesia are removed. The solutions typical of hydrothermal metamorphism are seen to possess a remarkable uniformity as to material added and subtracted despite differences in material acted on. Iron, sulphur, potassa, water, and quite often silica are added, while soda, lime, and magnesia are removed. The most significant chemical distinction appears to rest on the association of introduction of potassa with hydrothermal alteration.

The contact metamorphism which has been under discussion, characteristically alters sediments, involves heat, and may involve the addition and subtraction of certain substances; hydrothermal metamorphism alters igneous rocks, involves somewhat less heat, and the addition and subtraction of certain substances, plus addition of potassa. Contact metamorphism is a constructive process; hydrothermal is one with destructive tendencies.

ORIGIN OF MINERALIZING SOLUTIONS.

The diorite porphyry occurring chiefly as laccoliths should, as Lindgren suggests, represent the original material of the intrusive which, because of its isolated position, solidified with little opportunity for differentiation. Its relative lack of mineralization may be similarly explained.

In the main mass of the stock with a connection maintained with the magma reservoir below, the opportunity for differentiation would be good. The large masses of green mica rock which rapidly become more extensive with depth represent the alteration of a basic differentiate of the porphyry stock. As this basic material separated out, probably by gravitative settling of the heavy minerals which crystallize first,[24] the upper portion of the mass must have become more and more acidic, and rich in mineralizers.

Two processes are important in the separation of the mineralizing solutions which are originally dissolved in the magma. One is relief of pressure due to upward movement, the other is crystallization due to cooling.

The common association of mineralizers with porphyries rather than abyssal rocks points to the importance of relief of pressure in this connection.

The crystallization and segregation of the basic material would concentrate the mineralizers in the acidic portions of the magma. Sufficient relief of pressure would permit them to take a vaporous form and thus in all probability become immiscible with the liquid magma. These gas bubbles might rise through the magma with considerable speed.

The changes would take place in the stock before the reservoir below was affected.

The mineralizing solutions would, in general, be pneumatolytic where they leave the solidifying magma, as it is greatly above the critical temperature of water, and water is considered an essential constituent of these solutions. Their continuance in a vaporous

[24] Bowen, N. J., *Jour. of Geol.*, Dec., 1915, Supp.

condition would be dependent on the temperature gradient from the still liquid magma through the surrounding rocks. As convection is vastly more effective than conduction in the outward transfer of heat, the time when the maximum temperature reaches a given point is a matter depending on the vicissitudes of each particular case. In so far as the solutions active at any given point are aqueous rather than vaporous, it would indicate their more or less distant source.

At some early stage in the mineralization a solidified outer shell would be formed about the intrusive magma, and the mineralizing solutions would pass through cracks in this shell. Owing to the slight susceptibility of fresh igneous rocks to the anamorphic changes of pneumatolytic alteration, any effects produced would be lost in the later hydrothermal alteration. Any vaporous solutions following hydrothermal alteration, however, might be expected to produce conspicuous results. The fact that such evidence of contact alteration minerals developed in the intrusive rock is of rare occurrence would indicate that the time of contact metamorphism is in general before that of hydrothermal.

The separating out of the mineralizing solutions is probably largely a gravitative effect. It is not surprising that the mineralizers show a preference for the upper portions of the intrusive mass. Butler[25] has shown statistically that apically truncated stocks are most favorable to mineralization. At Morenci the mineralization is localized at the two points where the Paleozoic series has been preserved by down faulting. These points represent the highest preserved portions of the porphyry stock. The greater fracturability of the sediments as opposed to the pre-Cambrian granite may also have influenced this localization. The lack of mineralization in the more deeply truncated stocks which has been brought out by Butler indicates that the final giving off of the mineralizing solutions is from the upper portions of the stock and not from the deeper seated underlying magma reservoir. Otherwise the lower portions of the stocks or surrounding sediments should show the effects of the passage of the solutions.

[25] Butler, B. S., Econ. Geol., Vol. 10, No. 2, p. 101, 1915.

Fracturing would be most intense at margins and pneumatolytic solutions would affect sediments if not the igneous rock, while if the solutions were in liquid form they would surely leave traces in the stock itself.

This is somewhat different from the conception of Spurr[26] in his theory of ore-deposition. He considers the ore solution and the intrusive rock associated with the ore-deposits common differentiates of a deep-seated magma, which may reach their final resting place more or less independently of each other. He considers the adjacent intrusive incapable of differentiation, and unimportant as a source of ore solutions. The evidence here outlined points to a tendency of mineralizing solutions to become concentrated in the upper portions of an intrusive stock, coincident with the concentration of more basic materials in deeper seated portions. This conception indicates the importance of geologically rapid differentiation in the nearby intrusive masses as opposed to differentiation in the deep-seated magma reservoir.

That material originally dispersed through the magma of the deep-seated reservoir and ultimately given off as mineralizing solutions may have first become concentrated in the uprising apophyses is not improbable. However, when it is considered that many stocks undoubtedly have great vertical extent and become larger with depth, it seems reasonable to suppose the magma of the stock itself competent to supply a great bulk of mineralizing material where conditions are especially favorable to its separation as seems to have been the case at Morenci.

The writer is indebted to the officials of the Detroit Copper Co., of Morenci, Arizona, for making possible the collection of material and for helpful suggestions.

[26] Spurr, J. E., Econ. Geol., Vol. 2, No. 8, p. 781, 1907.